

# Probing Inflation and Dark Energy with the Cosmic Microwave Background

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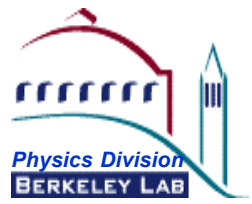
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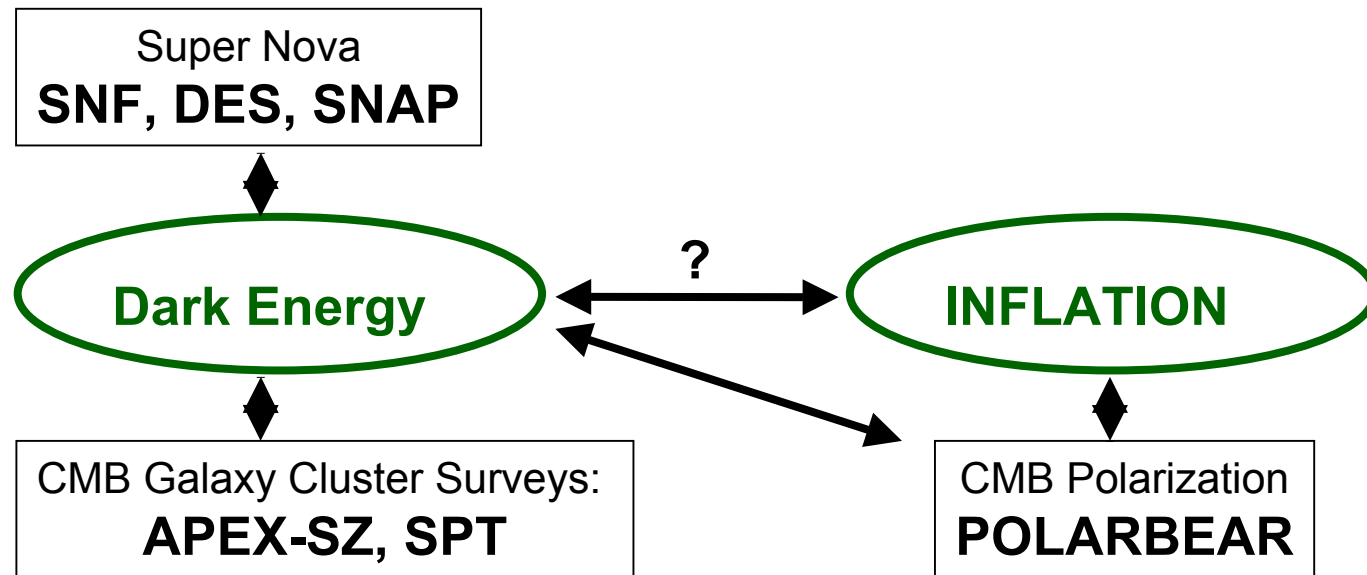
# HEP-Cosmology Connection

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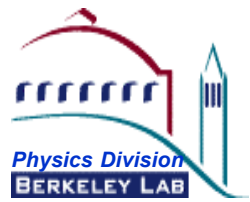
- Common Questions:
  - What happens at the highest energies?
  - What are the fundamental particles?
  - How do we unify the forces?
- Cosmology: a new tool
  - Highest Energies  $\Rightarrow$  Early Universe
  - Test masses probe gravity, e.g. Dark Energy
  - Tests of String Theory

# A Coherent Program



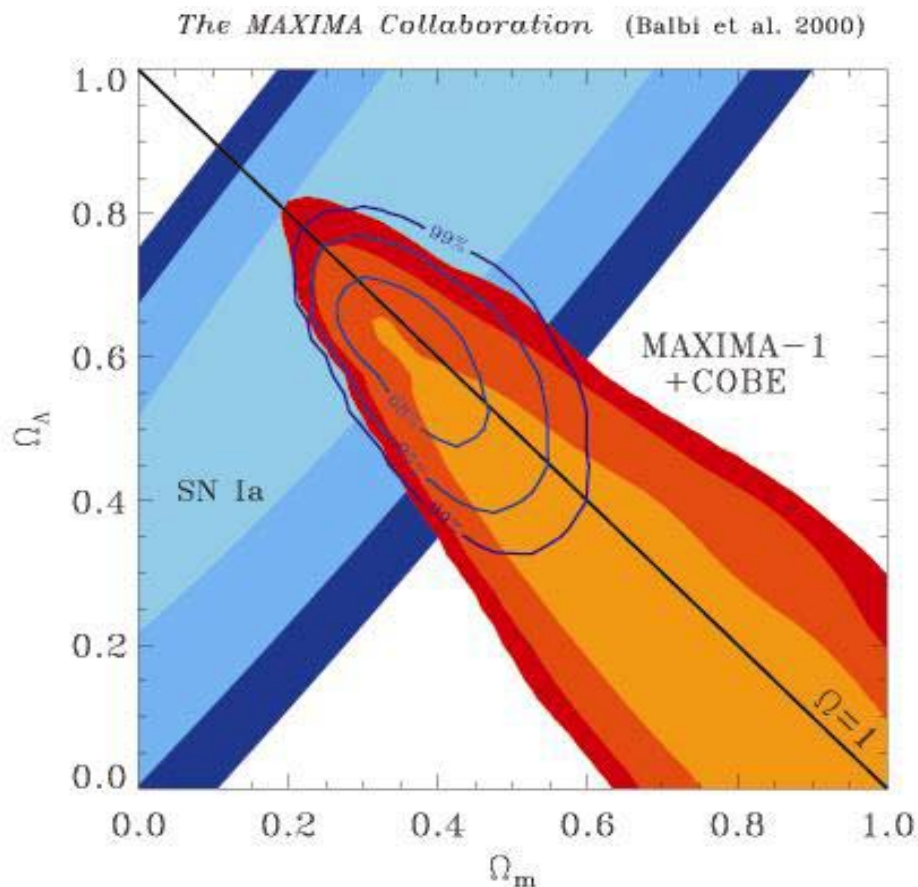
# LBNL/Campus Partnership

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- Integrated program combines efforts at LBNL + UCB
  - Complementary strengths of National Lab and University
- Strong program in theory and data analysis
  - Collaboration with NERSC
  - Strong role on Planck satellite analysis
- New instrumentation enables new experiments
  - APEX-SZ, South Pole Telescope - LBNL building array readout
    - Galaxy Cluster Search - probe Dark Energy
  - POLARBEAR - DOE lead role
    - CMB Polarization - probe Energy Scale of Inflation

# Berkeley CMB Experience

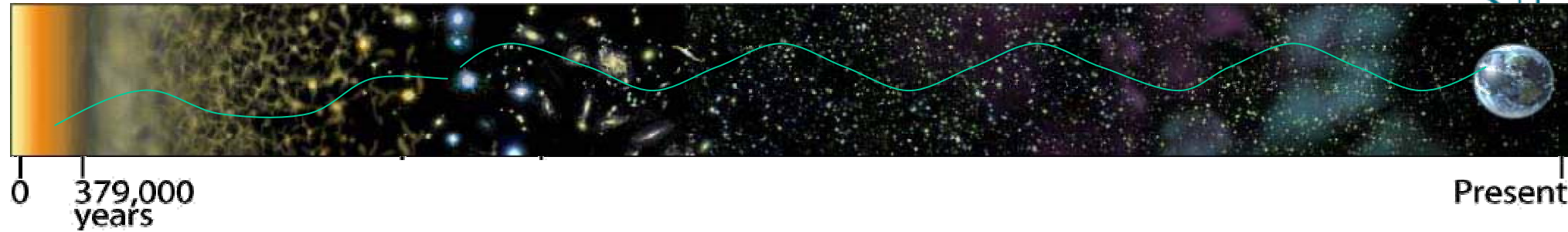


- MAXIMA: Strong Role in establishing peaks
  - Low systematic uncertainties
- Flat Geometry
  - => Critical for Dark Energy
- All Agencies: DOE, NSF (CfPA), NASA

# Galaxy Cluster Searches with the Sunyaev-Zel'dovich Effect

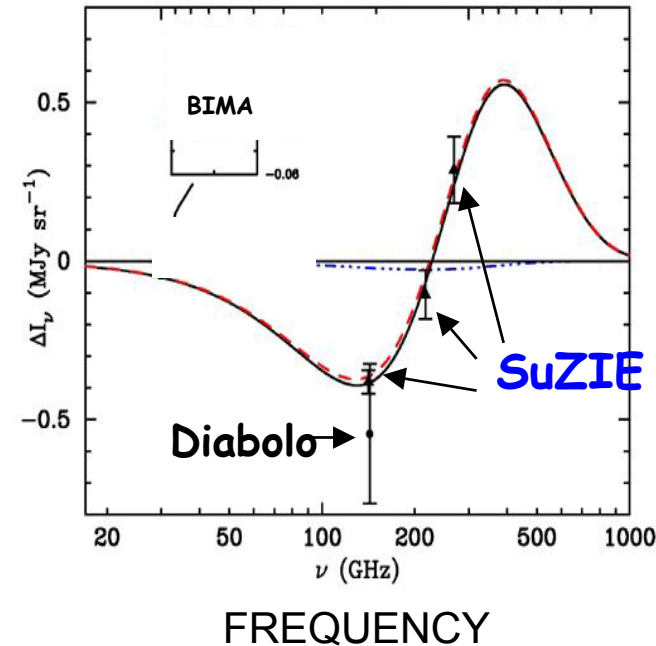
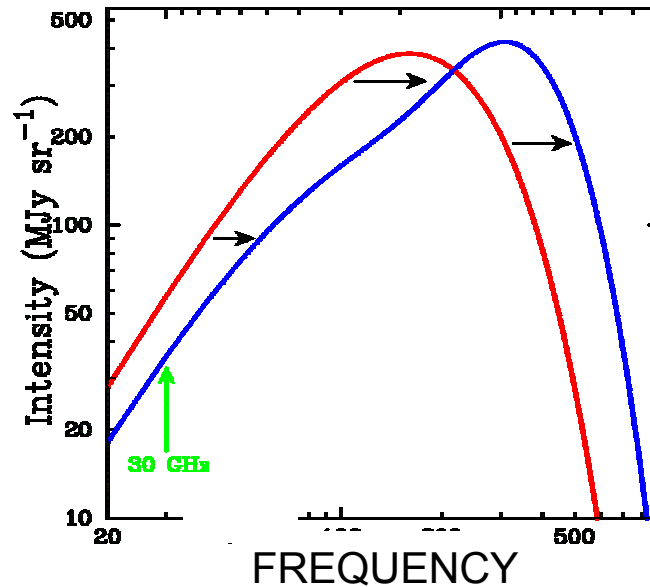


# The Sunyaev-Zel'dovich (SZ) Effect



CMB photons are used as backlight to structure in the universe.

- 1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy—the *Sunyaev Zeldovich Effect*.
- Tool for mapping expansion history
- Signal independent of red shift



# Atacama Pathfinder Experiment (APEX-SZ)



UC Berkeley/LBNL,  
MPI-Bonn/Munich,  
Cardiff

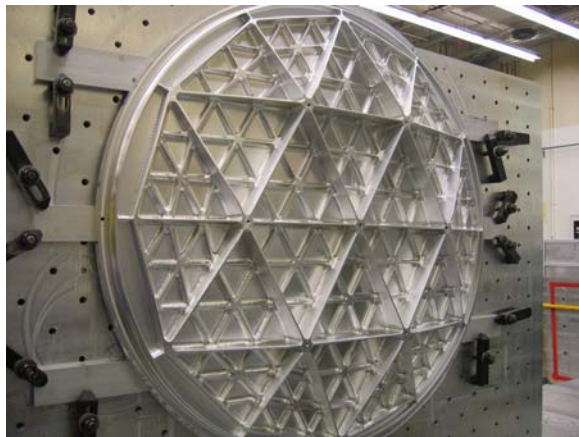
- 16,500 feet in Chilean Andes.
- 12m on-axis ALMA prototype
- Shared multi-user

## Berkeley SZ Receiver:

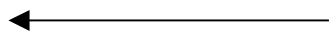
- 330 Bolometer array
- funded by NSF Astronomy
- Discover 4000 Clusters/2yrs
  - Mass limit  $> 4 \times 10^{14} M_0$
- First Light *Spring 2005*.
- LBNL responsible for readout
- Probe of Dark Energy



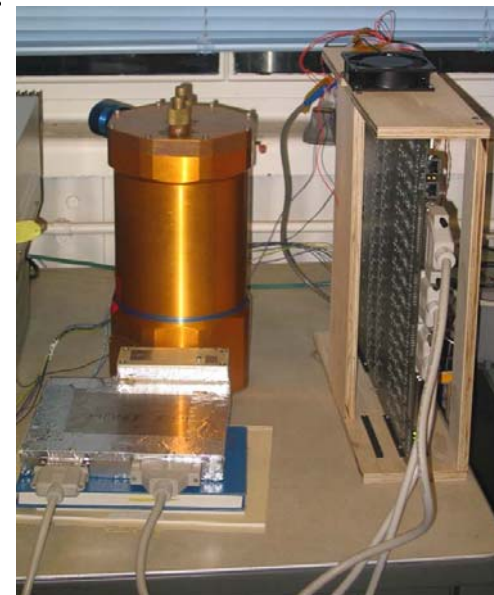
# New APEX Hardware



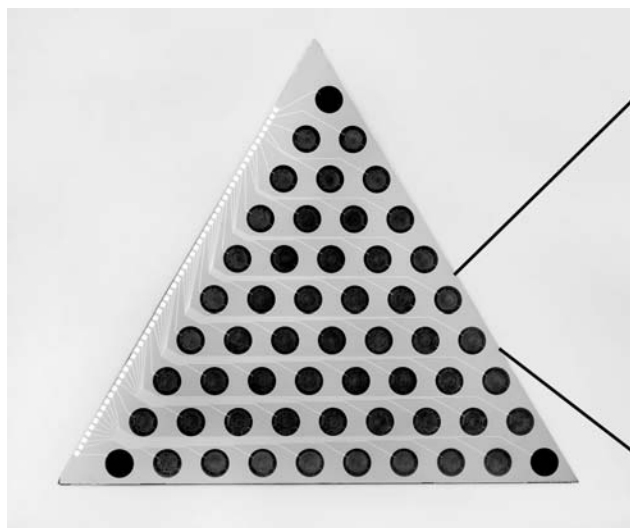
1.3 m diameter tertiary mirror  
(LBNL Machine Shop)



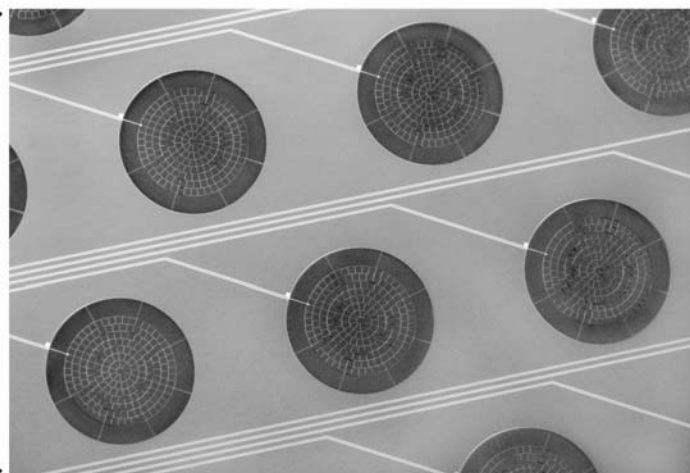
Bolometer Array  
Prototype



End-to-end test  
of readout @  
LBNL

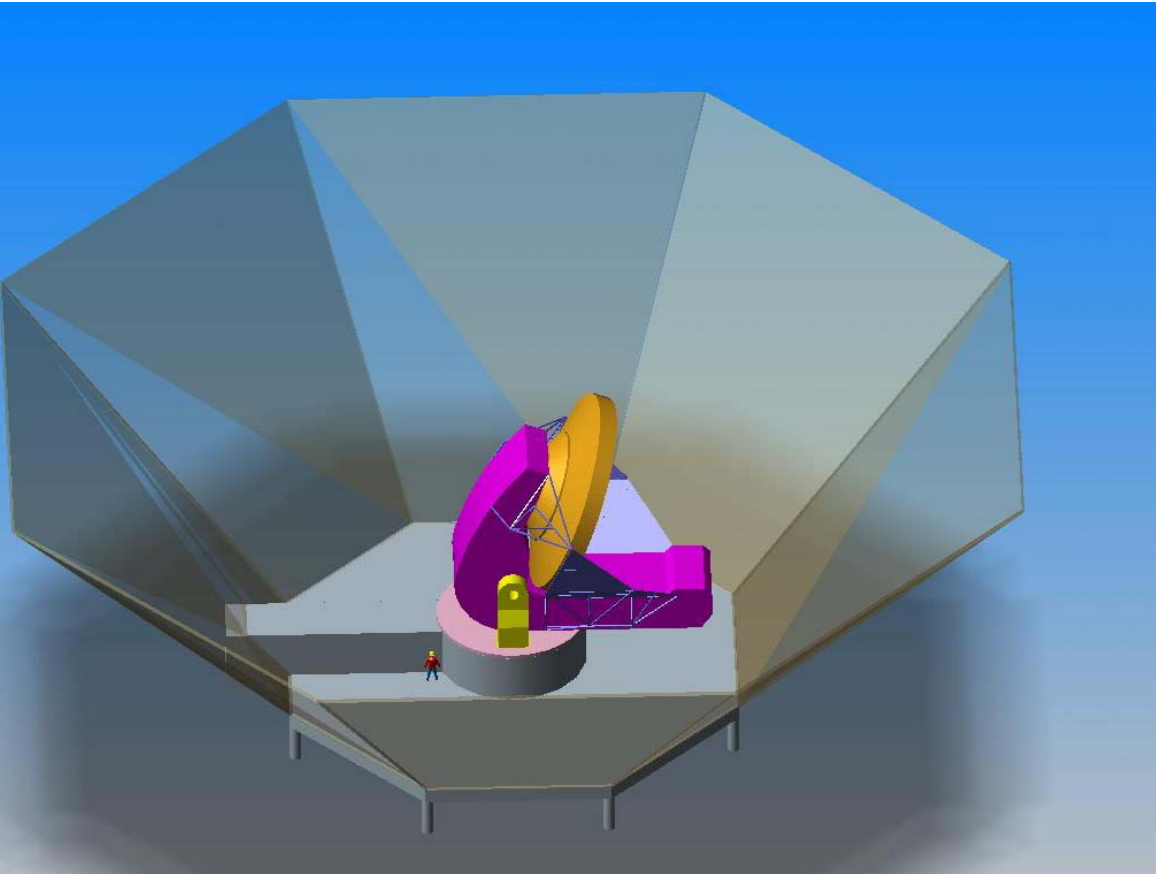


7.5 cm



5 mm

# South Pole Telescope



10m Telescope with ground shield

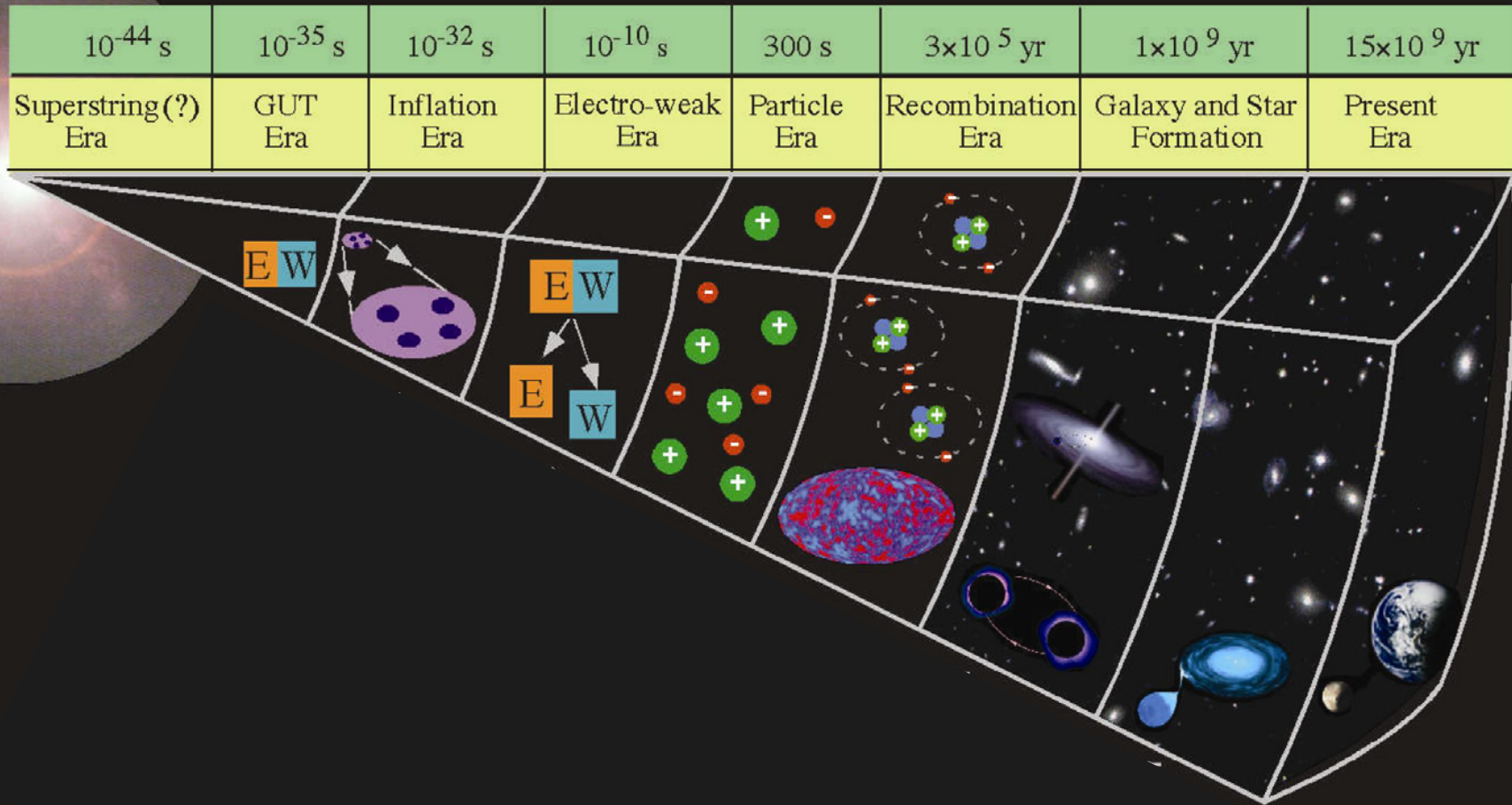
- $10^4$  Clusters (dedicated survey)
- Optical follow-up:
  - proposed Dark Energy Survey (FNAL, NOAO ...)
  - to use LBNL CCDs
- Funded by NSF OPP
- First light 2007
- LBNL responsible for readout

Participating Institutions:  
U. Chicago, UC Berkeley,  
Case Western, CfA,  
Univ. Illinois, LBNL

# CMB Polarization

# Big Bang

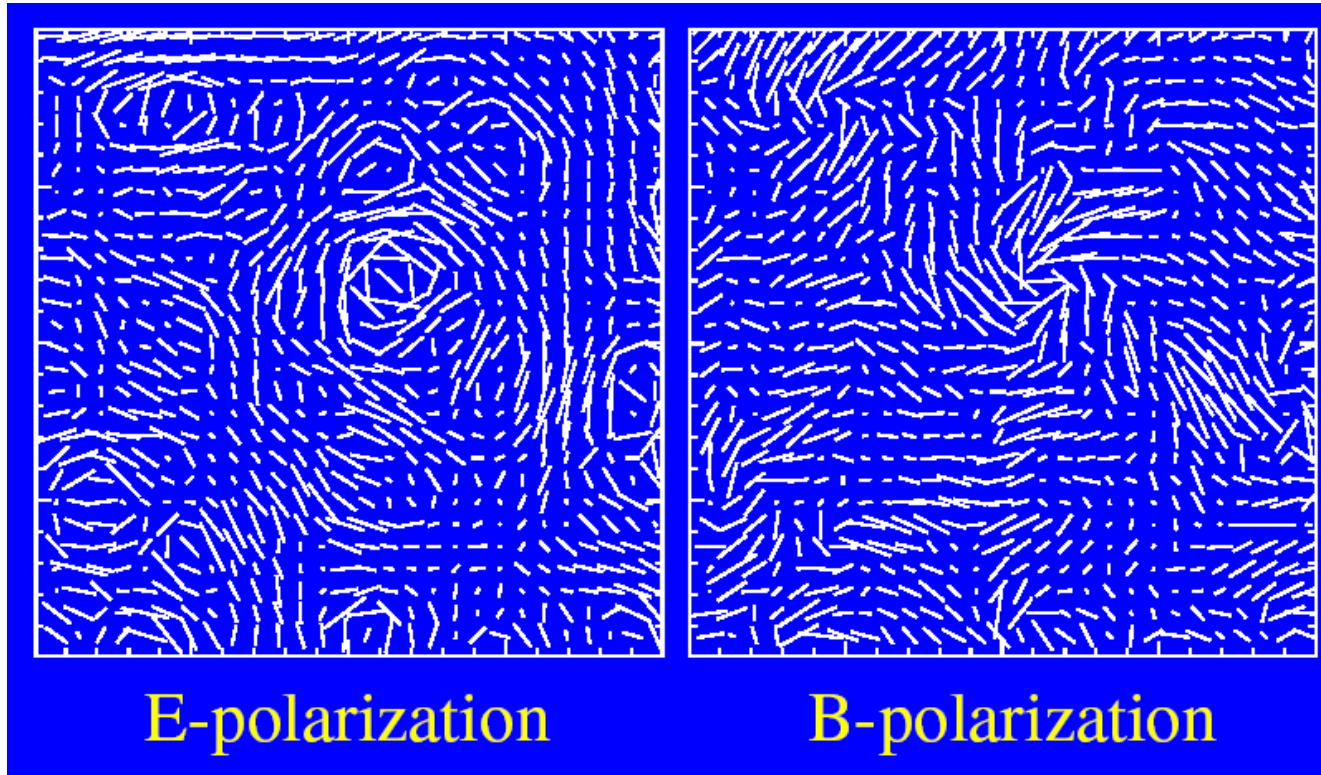
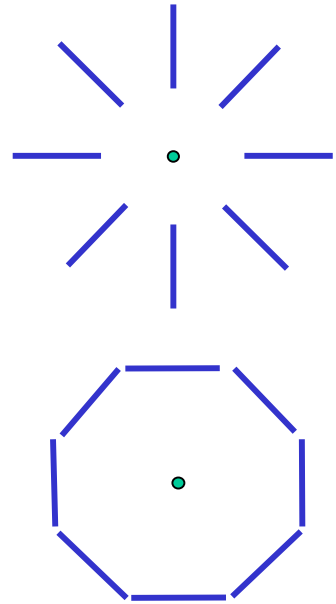
Time →



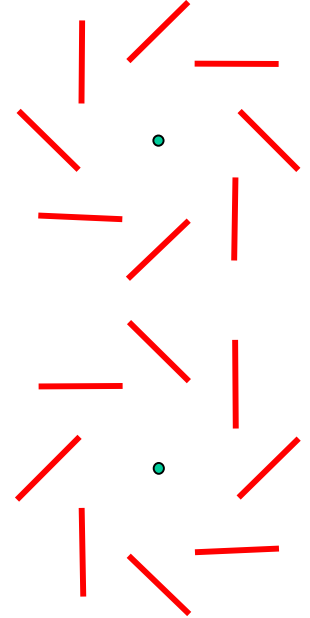
# Polarization Patterns

- Polarization Generation by Thompson Scattering

E-mode



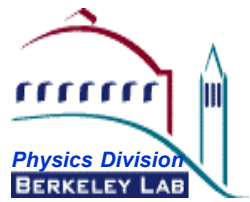
B-mode



Wayne Hu

- Density fluctuations give **scalar** perturbations  $\Rightarrow$  E-mode
- Gravity waves give **tensor** perturbations  $\Rightarrow$  B, E modes

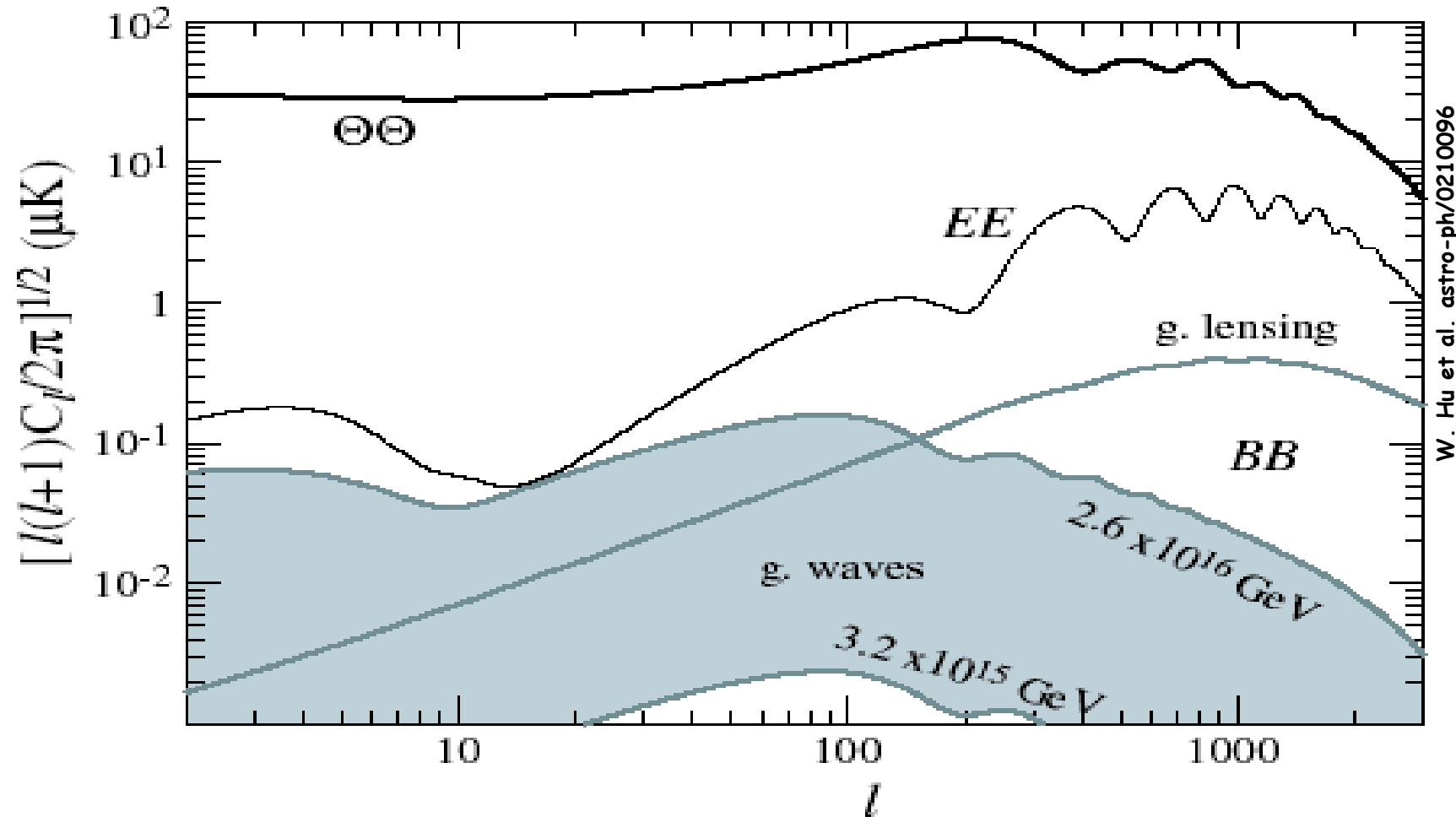
# Gravity Waves from Inflation



- Gravity waves put stress on photon-baryon fluid
  - Generation of B-mode polarization
- Detection  $\Rightarrow$  “smoking gun” of inflation
- Amplitude of B-mode gives Energy Scale
  - One possibility: GUT level  $10^{16}$  GeV
  - 12 orders of magnitude higher energy than accelerators!
- Quantum Gravity Regime
  - Observable evidence of String Theory?

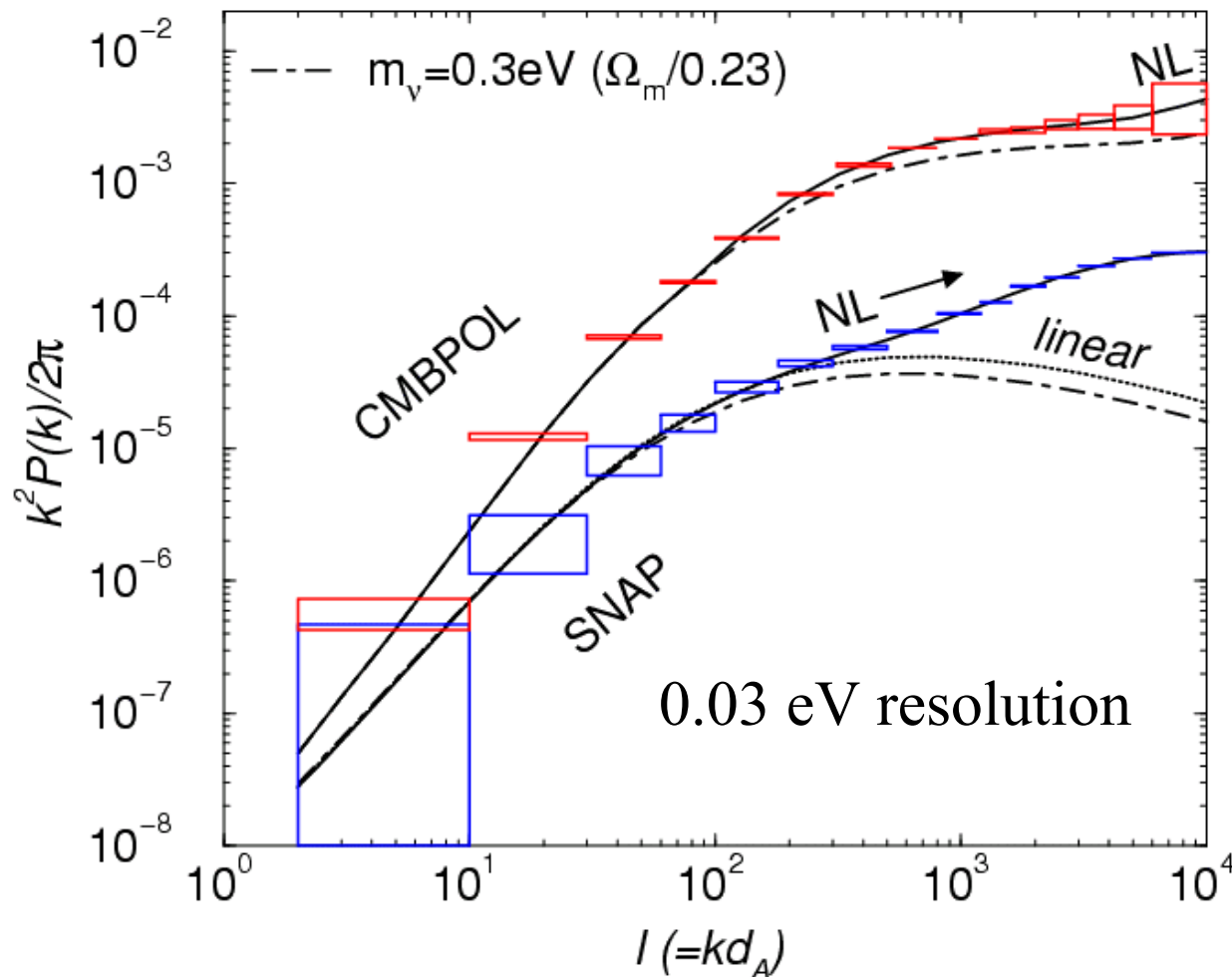


# CMB Polarization Spectra



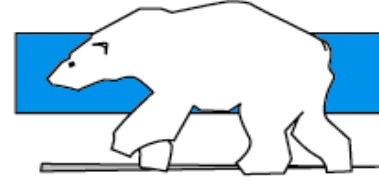
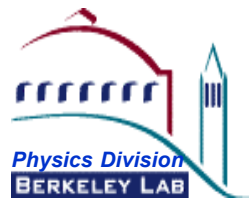
We need a large increase in sensitivity!

# Sum of Neutrino Masses from Lensing





# POLARBEAR (LBNL, UCB, UCSD)

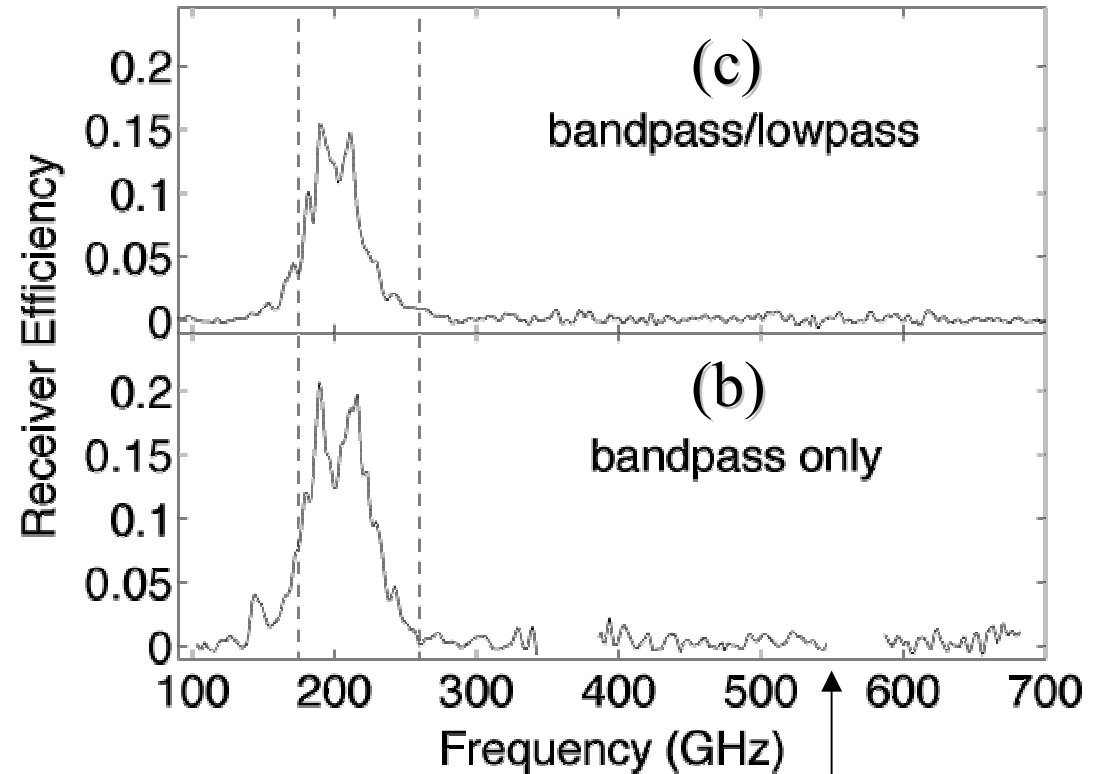
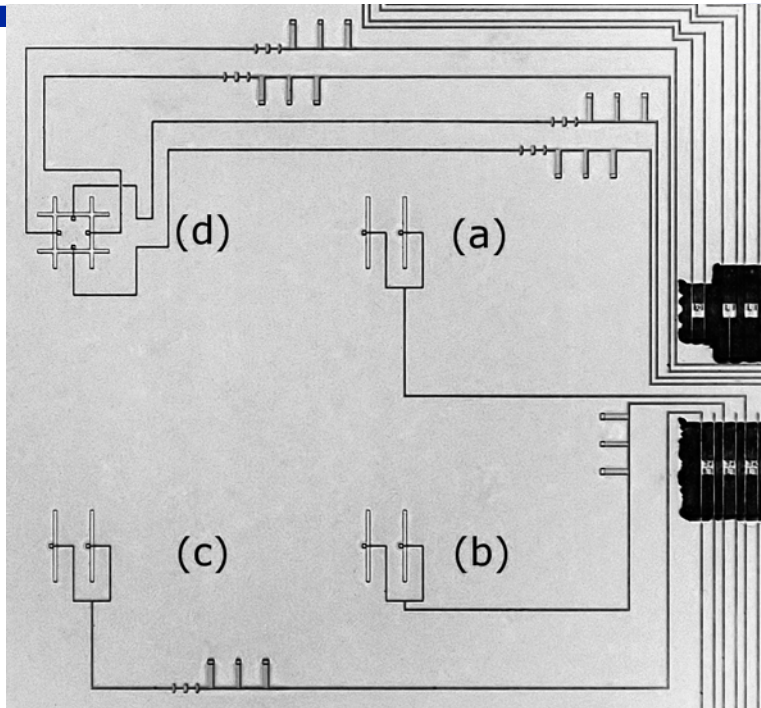


- Ground-Based 3 meter Telescope at UC Research Station on White Mountain
  - Optimized for CMB Polarization
    - Characterize E-modes
    - Search for B-modes
- Novel Technology
- Ready for Construction
  - R&D under LDRD funding
  - Positive Review from SAGENAP
  - \$6M over 5 years

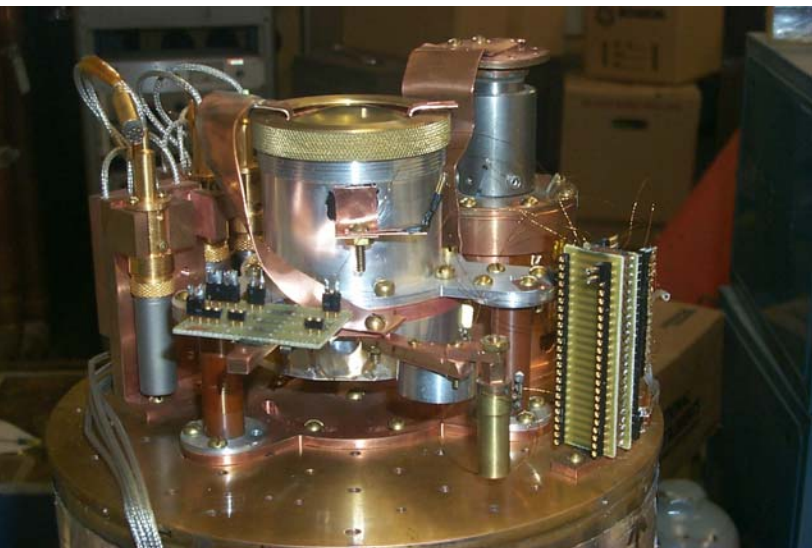
QuickTime™ and a  
TIFF (LZW) decompressor  
are needed to see this picture.

3m Telescope Design

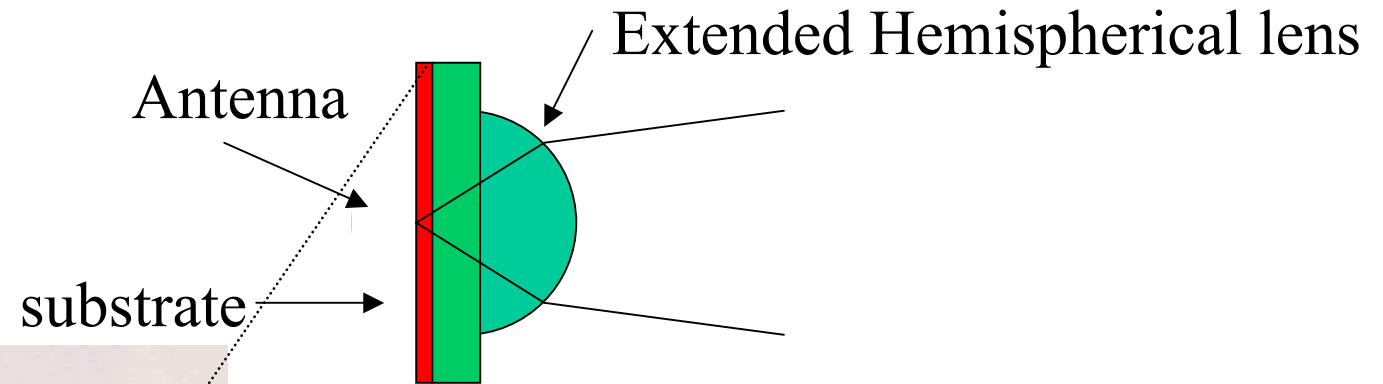
# New Technology: Radiometer on Chip



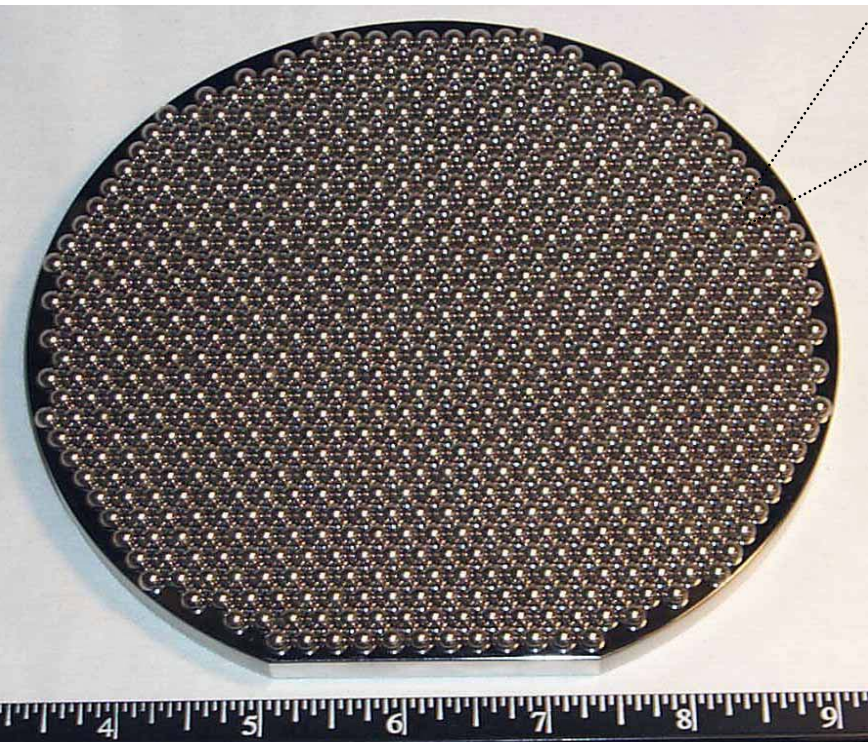
Metal mesh low pass



# Monolithic Array with Lenslets



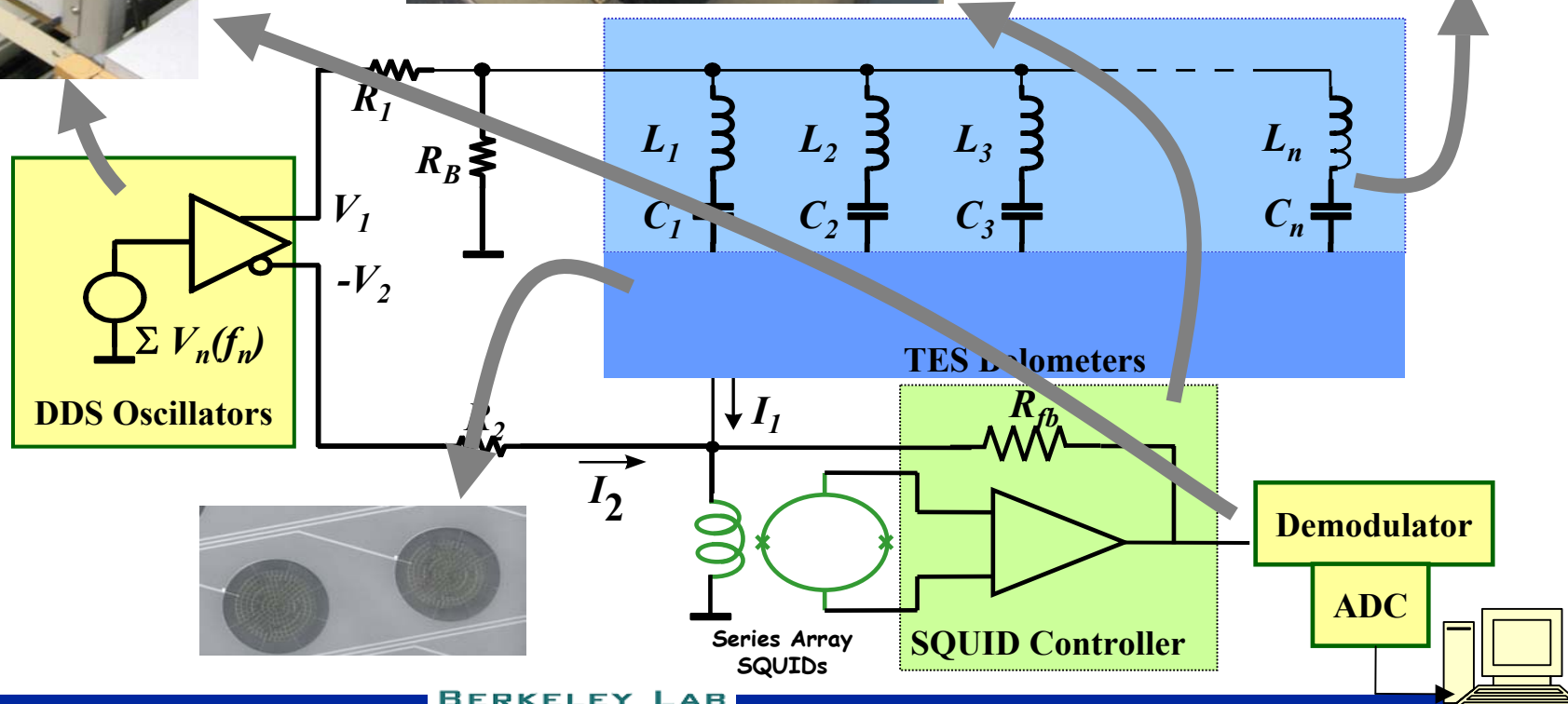
- POLABEAR-I 320 detectors
- POLARBEAR-II 1200 detectors



# Frequency Domain Multiplexer



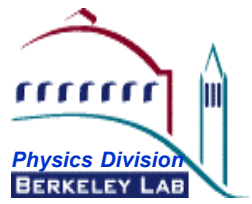
test chip of 8-channel  
Multiplexer (LBNL,  
UCB, TRW)





# Technology Development

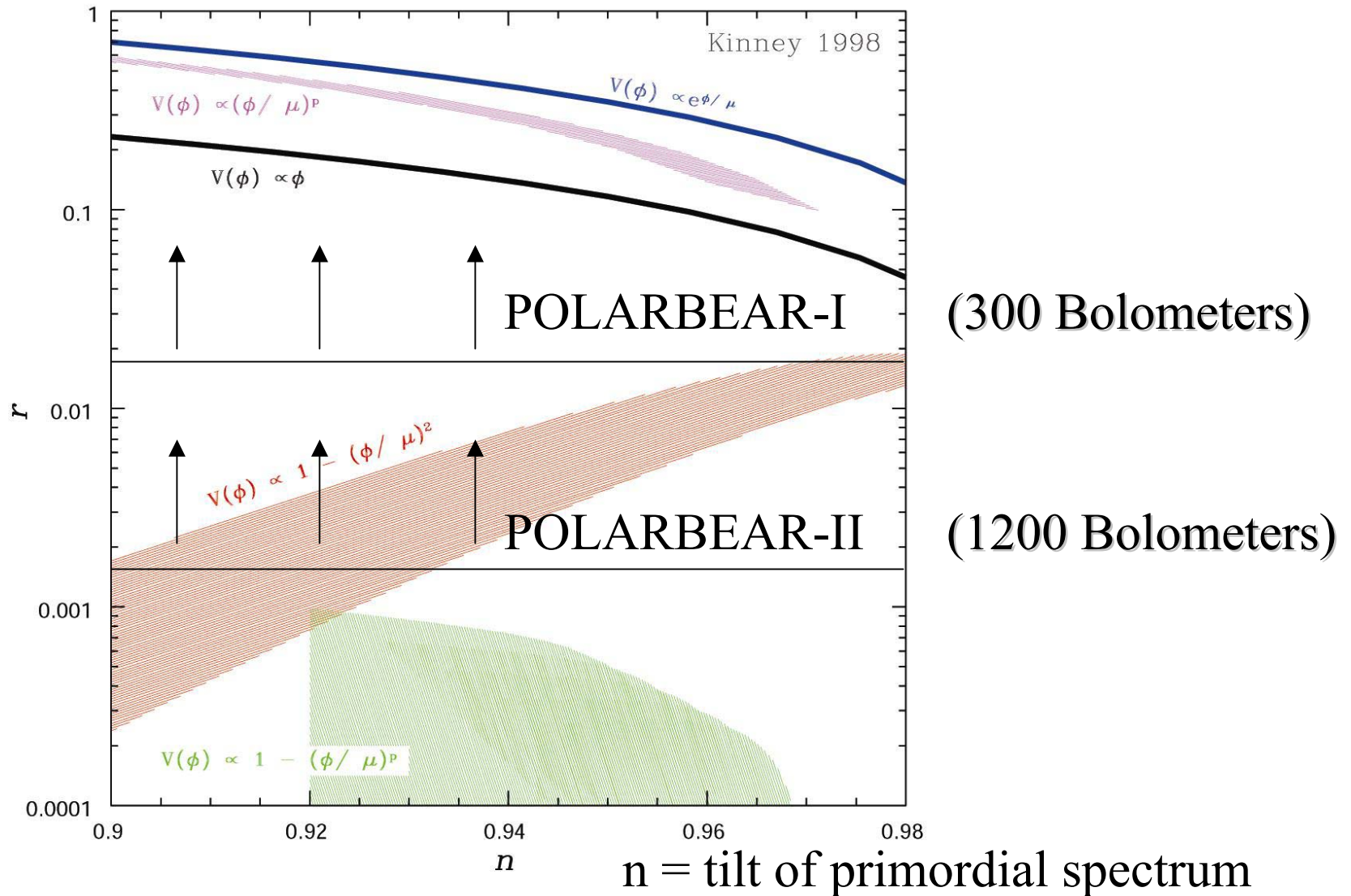
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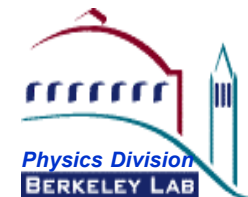
- LBNL and Campus work as one group
- Novel LBNL contributions
  - current summing MUX architecture + design
  - shunt feedback SQUID amplifier
  - theory + process for selecting SQUID parameters
  - computer-controlled multi-channel SQUID electronics
  - multi-channel demodulator, digitizer + data readout
    - Direct Digital Synthesis low-noise carrier generators
    - high dynamic range readout
- LBNL responsible for APEX-SZ and SPT readout

# POLARBEAR Statistical Errors

$r$  = tensor to  
scalar ratio

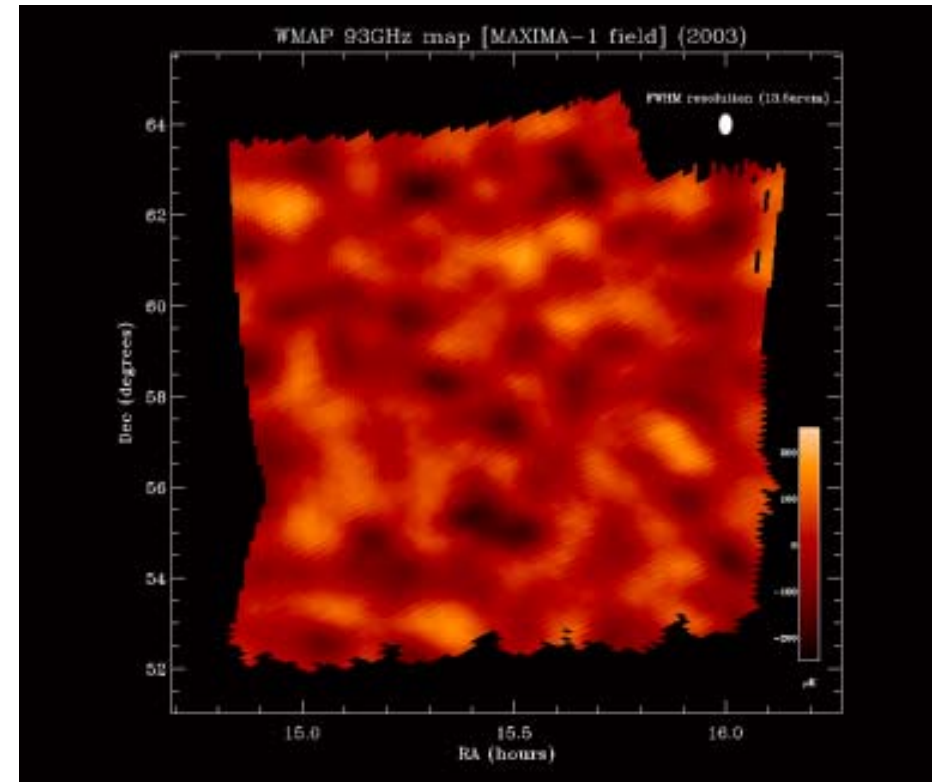
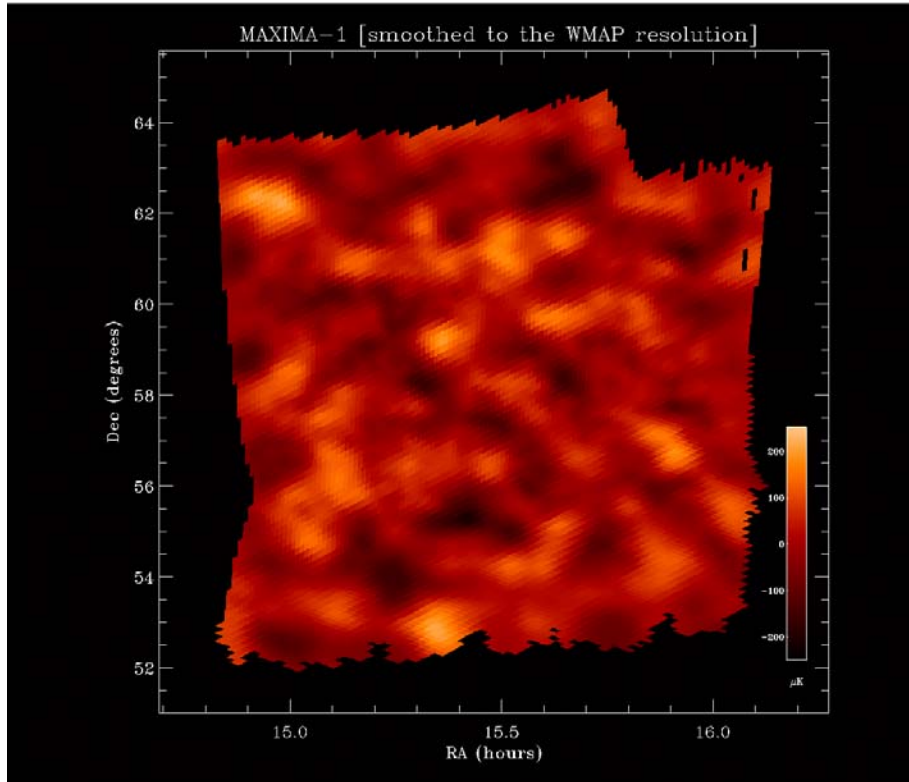


# Systematic Uncertainties



- Observation Strategy
  - Polarization Modulation
    - POLARBEAR: dual-modulation
      - differencing at pixel
      - Half Wave Plate
- Optics
  - polarization purity, sidelobe response
    - POLARBEAR: optimized for polarization measurements
- Foregrounds
  - Dust, Synchrotron
    - POLARBEAR: multi-frequency measurements

# MAXIMA and WMAP

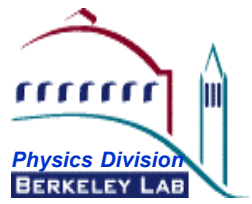


## Statistically Consistent Measurements



# CMB Polarization Satellite

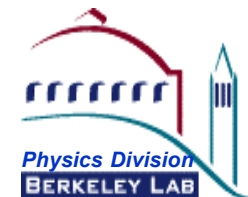
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- One of three “Einstein Probes” will be “CMBPOL”
- Berkeley/LBNL/CIT/JPL et al. in Study Phase
- LBNL infrastructure allows strong role for Berkeley
  - Critical mass for large project scale
- POLARBEAR : testbed for potential CMBPOL technology + observations

# SAGENAP Report

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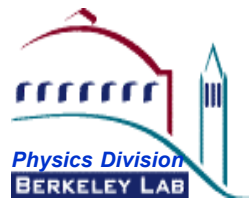


“In Summary, POLARBEAR Represents a novel and highly promising technique to attack the important scientific questions addressed by measurements of polarization of the CMB. The group is strong and it has a good track record.”

“We believe POLARBEAR is a project that merits funding and it should be considered by the agencies in the broader picture of the future of CMB measurements to be provided by the [tri-agency] CMB Roadmap study.”

# LBNL and Future CMB Experiments

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- LBNL has an irreplaceable role in the CMB Field
  - Expertise with large-scale detector systems
  - Expertise with large data sets
- Current: LBNL responsible for array readout
  - APEX, SPT
- Future: POLARBEAR
  - Lead role for DOE
  - A leap in capability beyond funded experiments
  - Positively reviewed proposal
  - Pathfinder for CMBPOL Satellite